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Specification and Drawings, as originally filed, with Application for Patent Serial No:  
**2,258,338**, on January 11, 1999, by **CERTICOM CORP.**, assignee of Farhad Pezeshki  
and Robert J. Lambert, for "Method and Apparatus for Minimizing Differential Power  
Attacks on Processors"

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## ABSTRACT

A method of masking a conditional jump operation in a cryptographic processor, wherein program execution jumps to one of two branches dependent on a first or second condition of a distinguishing value  $V$  relative to a reference wherein the reference is bounded by an upper limit  $V_{\max}$  and a lower limit  $V_{\min}$ . The method comprising the steps of determining the location of a conditional jump and inserting code thereat for executing instructions to change program execution to a respective one of the two branches by using said distinguishing value and a base address to compute a target address, wherein for each evaluation of said condition a different number of instructions are executed, thereby minimizing the effectiveness of a differential power attack.

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## METHOD AND APPARATUS FOR MINIMIZING DIFFERENTIAL POWER ATTACKS ON PROCESSORS

This invention relates to cryptographic systems and in particular to a method and  
5 apparatus for minimizing successful power analysis attacks on processors.

### BACKGROUND OF THE INVENTION

Cryptographic systems generally owe their security to the fact that a particular piece of  
information is kept secret, without which it is almost impossible to break the scheme. This  
10 secret information must generally be stored within a secure boundary, making it difficult for  
an attacker to get at it directly however, various schemes or attacks have been attempted in  
order to obtain the secret information. Of particular risk are portable cryptographic tokens,  
including smart cards and the like. Of the more recent attacks performed on these particularly  
vulnerable devices are simple power analysis, differential power analysis, higher order  
15 differential power analysis and other related techniques. These technically sophisticated and  
extremely powerful analysis tools can be used by an attacker to extract secret keys from  
cryptographic devices. It has been shown that these attacks can be mounted quickly and can  
be implemented using readily available hardware. The amount of time required for these  
attacks depends on the type of attack and varies somewhat by device. For example it has been  
20 shown that a simple power attack (SPA) typically take a few seconds per card, while the  
differential power attacks (DPA) can take several hours.

Encryption operations are performed in a processor operating in a sequential manner  
by performing a sequence of fundamental operations, each of which generates a distinct  
timing pattern. Laborious but careful analysis of end-to-end power waveforms can  
25 decompose the order of these fundamental operations performed on each bit of a secret key  
and thus be, analyzed to find the entire secret key, compromising the system.

In the simple power analysis (SPA) attacks on smart cards and other secure tokens, an  
attacker directly measures the token's power consumption changes over time. The amount of  
power consumed varies depending on the executed microprocessor instructions. A large  
30 calculation such as elliptic curve (EC) additions in a loop and DES rounds, etc, may be

identified, since the operations performed with a microprocessor vary significantly during different parts of these operations. By sampling the current and voltage at a higher rate, i.e., higher resolution, individual instructions can be differentiated.

5 The differential power analysis attack (DPA) is a more powerful attack than the SPA and is much more difficult to prevent. Primarily, the DPA uses statistical analysis and error correction techniques to extract information which may be correlated to secret keys, while the SPA attacks use primarily visual inspection to identify relevant power fluctuations. The DPA attack is performed in two steps. The first step is recording data that reflects the change in power consumed by the card during execution of cryptographic routines. In the second step,  
10 the collected data is statistically analyzed to extract information correlated to secret keys. A detailed analysis of these attacks is described in the paper entitled "Introduction to Differential Power Analysis and Related Attacks" by Paul Kocher et al.

Various techniques for addressing these power attacks have been attempted to date. These include hardware solutions such as providing well-filtered power supplies and physical  
15 shielding of processor elements. However, in the case of smart cards and other secure tokens, this is unfeasible. The DPA vulnerabilities result from transistor and circuit electrical behaviors that propagate to expose logic gates, microprocessor operation and ultimately the software implementations.

In software implementation of cryptographic routines, particularly on smart cards,  
20 branches in program flow are particularly vulnerable to power analysis measurements. Generally, where the program flow reaches a branch, then based on some distinguishing value  $V$ , one of two branches of the program is executed. To distinguish between the two possible cases,  $V$  is compared with a threshold value and a jump to one of two locations is executed as a result of the comparison. This is illustrated by referring to figure 1, where a flow diagram  
25 showing the implementation of a typical conditional jump according to the prior art is shown generally by 10. Generally a conditional jump implements an "IF *condition* THEN *statement1* ELSE *statement2* " clause. In this case, the flow diagram indicates a scenario where a distinguishing value  $V$  varies within a range and the *condition* is whether a threshold value  $TH$  is crossed by the distinguishing value  $V$  or not. The threshold  $TH$  is a random  
30 number between an upper limit and a lower limit  $V_{MAX}$  and  $V_{MIN}$ , respectively. Thus, it

may be seen in figure 1 if  $V < TH$  the program executes *statements1* or if  $V \geq TH$ , the program executes *statements2*. This may be repeated for all values of  $V$  from  $V_{MIN}$  to  $V_{MAX}$ .

As outlined earlier by utilizing a simple power analysis technique, it is possible for an observer to distinguish whether the "IF" branches or the "ELSE" branch is being executed. This however, does assume that the *statements1* and *statements2* consist of two identical sets of instructions that serve different purposes. Power or current consumption measurements on some smart cards can reveal which branch was taken. In some cases, some status flags on the chip may be set or reset. These flags may also be used for SPA.

Accordingly, there is a need for a system for reducing the risk of a successful power analysis attacks and which is particularly applicable to current hardware environments.

#### SUMMARY OF THE INVENTION

It is an object of this invention to provide a method for minimizing power analysis attacks on processors.

In accordance with this invention there is provided a method of masking a conditional jump operation in a processor, wherein program execution jumps to one of two branches dependent on a first or second condition of a distinguishing value  $V$  relative to a reference value and wherein the reference is bounded by an upper limit  $V_{max}$  and a lower limit  $V_{min}$ , the method comprising the steps of :

determining the location of a conditional jump; and

inserting code thereat for executing instructions to change program execution to a respective one of the two branches by using said distinguishing value and a base address to compute a target address, wherein for each evaluation of said condition a different number of instructions are executed, thereby minimizing the effectiveness of a differential power attack.

In a further embodiment the distinguishing value is combined with a random value, thereby adding a random number of instructions on every condition evaluation.

## BRIEF DESCRIPTION OF THE DRAWINGS

These and other features of the preferred embodiments of the invention will become more apparent in the following detailed description in which reference is made to the appended drawings wherein:

5           Figure 1 is schematic diagram of a conditional operation;

          Figure 2 is part of a computer program according to an embodiment of the present invention;

          Figure 3 is part of a computer program according to a further embodiment of the present invention;

10          Figure 4 is part of a computer program according to a still further embodiment of the present invention; and

          Figure 5 is a flow diagram illustrating another embodiment of the invention.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

15          Referring to figure 2, a schematic diagram of a method for masking conditional jump statements in a computer program, according to an embodiment of the present invention, is shown generally by numeral 50. We assume that the following code fragments are executed by a processor and that a distinguishing value *V* varies within a known range and the *condition* is whether a threshold value *TH* is crossed by the distinguishing value *V* or not.

20   The threshold *TH* is a random number in the known range having an upper limit and a lower limit *VMAX* and *VMIN*, respectively. In a generalized embodiment, the method comprises the steps of identifying a location for a conditional jump operation, and inserting at the location a call 52 to a subroutine 54, the subroutine 54 including instructions for changing the return address of the subroutine to one of two program branches to execute branch

25   *statements1* or branch *statements2* in response to the result of a comparison of the distinguishing value *V* to the threshold value.

          As may be seen in figure 2, the location of the conditional jump that is replaced is identified by code block a. The subroutine is identified as IRRITATE\_1 (54) and includes code blocks identified as b, c, d and e. The code block c includes a first and second sections

30   56 and 58, respectively. The start address of the second section 58 is predetermined and is

indicated by the value `KNOWN_DISPLACEMENT`. The start address of the first section 56 is then determined by the difference between `KNOWN_DISPLACEMENT` and the upper limit of the distinguishing value `V`. The first section 56 consists of a series of unconditional jumps to an address `L1` and the second section 58 consists of a series of unconditional jumps to an address `L2`. The locations `L1` and `L2` contain code for returning program flow to execute *statements1* and *statements2* respectively. The code block `b` included in the subroutine `IRRITATE_1` includes code for computing a difference between the `KNOWN_DISPLACEMENT` address and the `THRESHOLD`. The resulting address is then added to the distinguishing value `V` to derive a target address location in one of the sections 56 or 58.

As may be seen in block `a` the distinguishing value `V` is preserved while calling the subroutine, which in turn does not contain any conditional jumps. In this subroutine we change the return address of the subroutine (which resides on the stack) depending on whether `V` is below or above `TH` in such a way that, after returning from the subroutine, the program will continue execution in the desired branch.

An addressing mode known as extended addressing is used to determine the target address. With extended addressing the address at which the execution of the program has to continue is computed as the sum of the content of two registers. For example `JMP @A+DPTR` in the assembly language of the Intel 8051 family means that the address at which the program execution has to continue is computed by adding the content of the accumulator `A` and the data pointer `DPTR`. Other processors may support similar mechanisms for addressing. The code fragments shown in figure 2 illustrate the method. To refer to lines of these code fragments we use labels consisting of a letter and a number. Thus to implement this method we have to specify:

- a) the address at which the block of code 56 is going to reside. That would be the address of the first `JMP L1`;
- b) the range of the distinguishing value `V`; and
- c) the maximum value of the random threshold `TH`. This maximum value or a value derived from it will define the size of the code block containing the `JMP L1` and `JMP L2` instructions.

The operation of the code fragments shown in figure 2 will be discussed below. The code fragments may be located within a loop, which sequentially changes the value of V in a given range for iterations of the loop. For example V may be the value of the loop counter. The goal is to continue execution at the label DO\_REAL, line d1, as long as  $V < \text{THRESHOLD}$  and continue execution of instructions at the label DO\_VOID, line e1, for  $V \geq \text{THRESHOLD}$ .

As mentioned earlier the THRESHOLD value is a random value within the known range of Vmin and Vmax. At line a1 the distinguishing value V is stored in the accumulator of the processor and the subroutine IRRITATE\_1 is called at line a2. The return address from this subroutine will be line a3, which is automatically stored on the stack by the processor.

The KNOWN\_DISPLACEMENT in line b1 is a constant value that specifies the beginning location of the second section 58 and indicates the address of line c9. Thus  $\text{KNOWN\_DISPLACEMENT} - V_{\text{max}}$  is the address of line c1, the beginning location of the first section 56.

In Block b the value of KNOWN\_DISPLACEMENT is stored in a register at line b1. Next at line b2 the register is updated with the difference of KNOWN\_DISPLACEMENT and THRESHOLD. This difference is moved to in DPTR at line b3. Thus, DPTR contains the address of one of the lines c1 through c8 in block c. For example for  $\text{THRESHOLD} = 3$  DPTR would point to line c6. Assume next V and thus the contents of the accumulator can vary from 0 (Vmin) to 7 (Vmax). Then since DPTR may vary from the address of c1 to c8, the address  $@A + \text{DPTR}$  computed at line b4 can vary from the address of line c6 through c12 as V varies from 0 to 7. Therefore, for  $V < 3$  the JMP L1 instructions in the first section will be executed and for  $V \geq 3$  the JMP L2 instructions in the second section will be executed.

The labels L1 and L2 point to addresses located at lines c17 and c21 respectively. In lines c17 through c19 the return address of the subroutine IRRITATE\_1 is retrieved and changed such that the program counter will point to line a3 after returning from the subroutine. In lines c21 through c23 the return address of the subroutine IRRITATE\_1 is also retrieved and changed such that the program counter will point to line a4 after returning from the subroutine. The simple jump instructions at lines a3 and a4



It may be noted that the actual distinction between the two branches to be taken is decided at lines c18 and c22 where the retrieved subroutine return address is changed to the appropriate line in block a. In the present embodiment values of 0 and 1 have been chosen since the redirection jump instructions were located immediately after the call instruction to the subroutine IRRITATE\_1, at lines a3 and a4 respectively. In other implementations different values with equal number of 1's in their binary presentation may be used so that the difference in the add operations at lines c18 and c22 is indistinguishable to an attacker. In this case an appropriate number of NOP's would be added to code block a in order to adjust the return addresses.

Furthermore, the jump instructions in lines a3 and a4, which redirect program flow to *statements1* and *statements2* respectively, should be placed at addresses with the same number of 1's in their binary representation. This would result in homogenous power consumption on the address bus while addressing these two different locations. The same precaution applies to the lines d1 and e1, the beginning location of *statements1* and *statements2* respectively. In addition, in line b2 special attention should be paid to the choice of values of THRESHOLD and KNOWN\_DISPLACEMENT to avoid changes in flags in the processors status word while the SUB instruction is being executed.

Referring to figure 3, a second embodiment of the present invention is shown generally by numeral 100. This embodiment also utilizes extended addressing as described earlier. Again, assembly language of the Intel 8051 family of processors is used to illustrate the method. For clarity the symbols op1 through op7 are used to represent program instructions. In this embodiment, the distinguishing value V is one of two distinct values Vmax and Vmin, rather than a range of values. Thus, the *condition* in this case is when the distinguishing value V is one or the other of the distinct values Vmax or Vmin. Once again a call to a subroutine is inserted at a conditional jump location, the subroutine including instructions for changing the return address of the subroutine to one of two program branches to execute branch *statements1* or branch *statements2* in response to the distinguishing value V being one of the two distinct values Vmax or Vmin.

As may be seen in figure 3, the location of the conditional jump that is replaced is identified by code block f. The subroutine is identified as IRRITATE\_2 (102) and includes

code blocks identified as blocks g and h. The code block h also includes first and second sections 106 and 108, respectively. Each of the sections contain a series of dummy operations op1 indicated at lines h1 through h7 and at lines h12 through h18. Each of the sections is terminated by a sequence of instructions for retrieving the return address of the subroutine IRRITATE\_2 and changing it such that the program counter will point to line f4 or f5 after returning from the subroutine. The lines f4 and f4 include jumps to one of the two branches indicated as block i and block j which contain *statements1* and *statements2* respectively.

The target destination address is comprised of two components, namely the distinguishing value V or a value derived from V and a random number MASKED\_RANDOM, that are added at line g1. The beginning address of the first and second sections are chosen such that this target address is either in the range of lines h1 through h8 or h12 through h19. Since, the second component of the target address is a random number, a random number of dummy operations will be executed before the return address of the subroutine IRRITATE\_2 is computed at lines h8 to h10 (or h19 to h21).

As in the previous embodiment the ADD values at lines h9 and h20 may be chosen to have the same hamming weight(number of 1's), with appropriate number of NOP instructions added to block f. In addition the jump instructions at lines f4 and f5 may be placed at addresses with the same number of one's. Additional JMP instructions may also be inserted between the lines h1 and h8 with a destination in the same segment.

This embodiment thus uses unconditional jumps instead of conditional jumps and adds a random number of dummy operations to the code. The former property is a countermeasure against SPA and the latter makes DPA attacks more difficult. In particular this embodiment adds a random mask or noise to the program execution path since the jump to a random address within a segment causes program execution of a random number of operations before one of the branches is executed. Therefore each time one of the branches is executed, the number of operations performed by the processor varies randomly making DPA attacks more difficult.

In the above embodiments, a subroutine is used to redirect program flow, however in figure 4, a simple series of jumps are used. The invention is thus not restricted to the embodiments shown.

Referring to figure 5 an embodiment of a method for masking a private key or secret  
 5 used in a cryptographic operation is shown generally by numeral 200. The method comprises the steps of dividing the key into a plurality of parts and combining with each part a random value modulo  $n$  (where  $n$  is the number of points on the elliptic curve) to derive a new part such that the new parts are combined to be equivalent to the original private key value and utilizing each of the individual parts in the operation.

10 As seen in figure 5, the cryptographic processor is initialized with the public key or secret value  $d$ . In computing a public key  $Q = dP$ , the secret key  $d$  is normally combined with the point  $P$  to derive  $dP$ . The value  $d$  is divided into a number of parts, eg  $d = b_{10} + b_{20}$ .

In a first step the  $b_i$ 's are initialized  $b_1 = b_{10}$  and  $b_2 = b_{20}$  such that  $d = b_{10} + b_{20}$ . These values of  $b_1$  and  $b_2$  are stored instead of  $d$ . Alternatively the  $d$  value may also be stored if so  
 15 desired, however in the case of a smart card where memory is limited this may not be desirable.

At a next step, a random number  $\pi$  is generated and the values  $b_1$  and  $b_2$  are updated as follows:

$$b_1 = b_1 + \pi \text{ mod } n$$

20 
$$b_2 = b_2 - \pi \text{ mod } n$$

The updated values of  $b_1$  and  $b_2$  are stored. Computation is then performed on the point  $P$  using the components  $b_1$  and  $b_2$  as follows:

$$dP \text{ mod } n = b_1P + b_2P \text{ mod } n$$

Thus assuming the value  $\pi$  is randomly generated for each session then an attacker is  
 25 unlikely to observe a predictable power signature.

In a typical application of the present invention a signature component  $s$  has the form:-

$$s = ae + k \text{ (mod } n)$$

where:

$P$  is a point on the curve which is a predefined parameter of the system;

30  $k$  is a random integer selected as a short term *private* or session key;

$R = kP$  is the corresponding short term *public* key;  
a is the long term private key of the sender;  
 $Q = aP$  is the senders corresponding public key;  
e is a secure hash, such as the SHA-1 hash function, of a message  $m$  and the short term  
5 public key  $R$ ; and  
n is the order of the curve.

The sender sends to the recipient a message including  $m$ ,  $s$ , and  $R$  and the signature is  
verified by computing the value  $R' = (sP - eQ)$  which should correspond to  $R$ . If the computed  
values correspond then the signature is verified. Both the secret keys in the above example  
10 may be masked using the method of the present invention.

Although the invention has been described with reference to certain specific  
embodiments, various modifications thereof will be apparent to those skilled in the art without  
departing from the spirit and scope of the invention as outlined in the claims appended hereto.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A method of masking a conditional jump operation in a cryptographic processor, wherein program execution jumps to one of two branches depending on a first or second condition of a distinguishing value  $V$  relative to a reference wherein the reference is bounded by an upper limit  $V_{\max}$  and a lower limit  $V_{\min}$ , the method comprising the steps of:
  - (a) determining the location of a conditional jump; and
  - (b) inserting code thereat for executing instructions to change program execution to a respective one of the two branches by using said distinguishing value and a base address to compute a target address, wherein for each evaluation of said condition a different number of instructions are executed, thereby minimizing the effectiveness of a differential power attack.
2. A method as defined in claim 1, said distinguishing value being combined with a random value, thereby adding a random number of instructions on every condition evaluation.

LINE#	SOURCE TEXT
1	TH = a random number between VMIN and VMAX
2	FOR V from VMIN to VMAX do
3	IF V < TH THEN
4	DO statements1                   {branch1}
5	ELSE
6	DO statements2                   {branch2}
7	OF

10

Figure 1

Line #	Source Text	Comment
a1 a2 a3 a4	MOV A,V CALL IRRITATE_1 JMP DO_REAL JMP DO_VOID ... ...	Block a
b1 b2 b3 b4	IRRITATE_1: MOV R0,KNOWN_DISPLACEMENT SUB R0,THRESHOLD MOV DPTR,R0 JMP @A+DTPR ... ...	Block b
c1 c2 c3 c4 c5 c6 c7 c8	JMP L1 JMP L1 JMP L1 JMP L1 JMP L1 JMP L1 JMP L1 JMP L1	Block c
c9 c10 c11 c12 c13 c14 c15 c16	JMP L2 JMP L2 JMP L2 JMP L2 JMP L2 JMP L2 JMP L2 JMP L2	
c17 c18 c19 c20 c21 c22 c23 c24	L1: POP A ADD #0 PUSH A RET L2: POP A ADD #1 PUSH A RET	
d1 d2	DO_REAL: Statements1 ... ...	Block d
e1 e2	DO_VOID: Statements2 ... ...	Block e

Figure 2

Line #	Source Text	Comments
f1 f2 f3 f4 f5 ... ...	MOV A,V MOV DPTR,MASKED_RANDOM CALL IRRITATE_2 JMP DO_REAL JMP DO_VOID ... ...	Block f
g1 g2 ...	IRRITATE_2: JMP @A+DPTR ... ...	Block g
h1 h2 h3 h4 h5 h6 h7 h8 h9 h10 h11	op1 op2 op3 op4 op5 op6 op7 POP A ADD #0 PUSH A RET	Block h
h12 h13 h14 h15 h16 h17 h18 h19 h20 h21 h22	op1 op2 op3 op4 op5 op6 op7 POP A ADD #1 PUSH A RET	
i1 i2 ...	DO_REAL: Statements1 ... ...	Block i
j1 j2 ...	DO_VOID: Statements2 ... ...	Block j

100

Figure 3



Line #	Source Text	Comments
	MOV A,V JMP IRRITATE_1 ... ...	Block k
	IRRITATE_1: MOV R0,KNOWN_DISPLACEMENT SUB R0,THRESHOLD MOV DPTR,R0 JMP @A+DTPR ... ... JMP DO_VOID JMP DO_VOID JMP DO_VOID JMP DO_VOID JMP DO_VOID JMP DO_VOID JMP DO_VOID JMP DO_VOID KNOWN_DISPLACEMENT: JMP DO_REAL JMP DO_REAL JMP DO_REAL JMP DO_REAL JMP DO_REAL JMP DO_REAL JMP DO_REAL JMP DO_REAL JMP DO_REAL	Block l
	DO_REAL: ... ...	Block m
	DO_VOID: ... ...	Block n

Figure 4

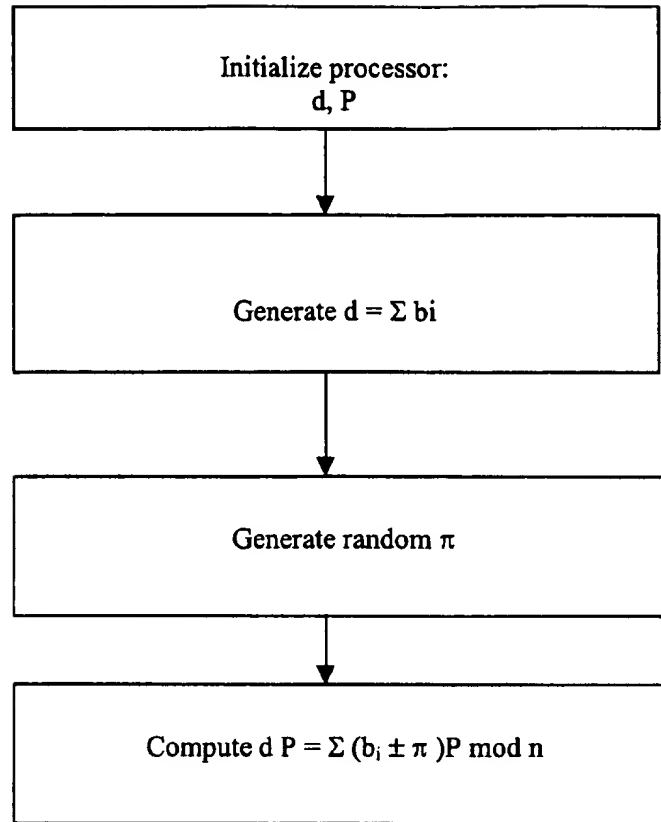


Figure 5